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FLUIDIZATION THEORY APPLIED TO THE LUNAR MARIA

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The possible significance of a gas-solid fluidization process in [redacted] shaping the moon is being studied at the NASA Goddard Space Flight Center. The process is referred to by geologists as "ash flow", or, less strictly, "nuée ardente"; the end product is variously referred to as an ignimbrite, an ash flow tuff, or in special cases as a welded tuff. It appears possible that this mechanism can explain at the same time the morphological features of the maria and the chemistry and age relationships of tektites. The latter are small glassy pebbles which are regarded as of lunar origin by workers at several places, including Goddard, Dr. Chapman's group at NASA Ames Research Center, and Dr. Chao's group at the U.S. Geological Survey.

The evidence that tektites are of lunar origin rests essentially upon two or three facts. First, they are clearly the result of an impact of an enormous meteorite on some planetary surface. Chao has shown that some tektites from the Far East contain the characteristic meteorite minerals kamacite, schreibersite and troilite. Any one of these alone would point strongly to a meteoritic origin; the presence of all three is decisive. The tiny spherules in which the minerals are found are apparently produced by impact of a meteorite. Similar spherules are found embedded in some very different looking spongy glass around terrestrial impact craters. The impact probably did not take place on the earth, first because of terrestrial materials containing a few tenths of a percent of water at the least. The water, if expanded under

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the heat of impact, would give rise to an extremely spongy structure which is seen in terrestrial impacts and is absent in tektites. Tektites are in fact among the driest materials known on earth. In the second place molten glass droplets produced by impact could scarcely be propelled through the atmosphere, even in the most violent impacts. As is well known from meteorite studies, objects of tektite size will be arrested by layers of atmosphere no thicker than those which exist above a height of 50 km. Hence the blast waves from the explosion must reach this height with velocity essentially undiminished, since otherwise the tektite will encounter undisturbed air. Alternatively, it is imaginable that the explosion itself will send the majority of its debris to this height, and so break a path for the tektite. We can calculate the size of an impact required to accomplish the first task; it is of the order of 10^{28} ergs, or something like one million megatons. To produce the Far Eastern tektites, which cover an area thousands of kilometers in both directions, we would expect a crater which would be visible even to the present day. The second possibility has not been calculated; it would also demand a very large crater.

If not from the earth, then the tektites are most likely from the moon, since they do not carry in them, as was pointed out by Viste and Anders, the Al^{26} which we would have expected to result from a voyage across interplanetary space. Moreover, Chapman and Adams have both drawn attention to the fact that the entry velocities of tektites are not likely

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to have been very high. They are reconcilable with arrival from the moon, but are not easily reconcilable with arrival from some other body.

The derivation of tektites from the moon presents an age problem, as pointed out by Tilton at the Geophysical lab of CIW and by Pinson and Schnetzler at MIT. Lead-uranium ages found for tektites by the former group, and especially the rubidium-strontium ages found by the MIT group, fall in the range of a few hundreds of millions of years. They are thus not to be reconciled with the age of the lunar surface as a whole, which is believed to be similar to the age of the solar system, on the order of a few thousands of millions of years. A lunar origin is only imaginable if there are portions of the moon's surface which are much younger than the rest. The logical place to look for young material on the moon is in the broad, flat, relatively crater-free maria. The maria are the dark areas on the moon which we see with the naked eye as making a sort of face. They have been explained by some workers as flows of dark lava; but at Cornell Dr. Gold has suggested that they are a sort of sediment resulting from the slow erosion of the moon's surface and the transport of the particles by electrostatic hopping. Neither of these explanations will do for the tektites. A dark lava would be basic in chemistry, and irreconcilable with the acid chemistry of tektites. The results of erosional processes on a very ancient landscape would be the formation of sediments whose Rb-Sr age, for example, would be just as great as that of the original materials. This difficulty has been frequently referred to as a major objection to the whole idea that tektites come from the moon.

If, however, we suppose that the maria are ash flow tuffs, then the picture changes. An ash flow tuff is a deposit of tiny pieces of volcanic glass emplaced by a process of fluidization. The hot glass releases steam, and in a thick bed (say 30 meters or so) the rising steam forces the particles apart slightly and cushions them from each other. As a result the bed becomes fluidized in the sense in which this word is used in engineering. The gas-solid combination becomes in effect a liquid of very low viscosity. It is capable of rolling down a shallow slope and spreading out like a liquid with a very nearly level top surface. The Valley of 10,000 Smokes in Alaska, which is a recent ash flow, had, when new, a surface that could be bicycled over. It is a fact that most ash flows are acid in their chemistry. They thus satisfy the most obvious requirements of the tektite hypothesis.

It turns out that the ash flow idea explains a good many other peculiarities of the maria. Gold, in 1955, drew attention anew to a fact mentioned earlier by Shaler, that the maria lack the characteristic scarps around the edges which are seen at the edges of a lava flow. These scarps are the final positions of a sort of retaining wall which a lava flow pushes ahead of it. The lava is rarely a nice liquid like water; the surface is almost always crusted over with congealed rock. The rock piles up ahead of the flow and builds a dam. The lava advances by breaking through the dam. The height is normally something like 10 or 20 feet. A line of this height on the moon would be rather easily detectable when the sun is low so that the shadows are 50 or 100 times as long as the height of the object. These scarps have been carefully searched for many times without success. Their absence is what we would expect if we were dealing with an ash flow.

When an ash flow spreads out over an existing carved-up terrain, the ash is deepest in the low places and shallowest in the high ones. After being deposited, the porosity tends to be squeezed out. In many ash flows the heat is retained in the lower levels for a long time. The tiny bits of glass are plastic enough so that the porosity is squeezed out, and the mass is welded to something like an obsidian. Even at smaller depths there is sintering. At the top surface there is a lowering which is greatest where the topography was originally lowest. The net result of this process is what F. R. Boyd, at the Geophysical Laboratory of CIW calls "exhumation of the topography," that is, a top surface which imitates the undulations of the ground with diminished amplitude.

On the moon there are numerous examples of craters which appear to project through the maria with the same roundness as other craters but with very much diminished heights. These drowned and half-drowned craters may, it seems to me, represent cases where there has been exhumation of the topography.

In some places on the moon we see markings which look like level beds. They can hardly be due to water, which, under vacuum conditions, promptly transforms itself to steam or ice; and no other liquid is probable. The suggestion has been made by Mrs. W. S. Cameron that these are ditches carved by the passage of ash flows. Such ditches are known in terrestrial events, especially the Kambara ash flow from the volcano Asama in Japan. An interesting question which is now under study is the possible role of the ash flow process in producing chemical differentiation. It turns out that on the earth the effect of an ash flow is sometimes to separate the crystals from the glassy portions of the volcanic ash. The crystals are larger and not so easily carried by the upflowing airstream. In industry the process is referred to as elutriation, that is, the removal of the fines. It is at least conceivable that by the process of elutriation some of the same effects are produced as those produced by terrestrial sedimentary processes. Quartz crystals are especially resistant to smashing in any sort of grinding process, and they therefore tend to be enriched in the portion of material which is left behind. Tektites correspond, as S. R. Taylor has repeatedly pointed out, not to any common type of igneous rock, but to an intermediate igneous rock whose silica content has been enhanced in some way or other. Conceivably the elutriation process involved in a lunar ash flow may provide the necessary mechanism.

This view of the nature of the maria suggests that some of the ridges found near Mare Imbrium, for example may represent obsidian slowly extruded through fissures in a manner which is common on the earth where ash flows are found. It suggests that the moon's interior is hot, and that the red spots observed near Aristarchus are in some way traces of surviving volcanism. These suggestions may well prove to be helpful in shaping future research on the surface of the moon.